



Effects of urban growth spatial pattern (UGSP) on the land surface temperature (LST): A study in the Po Valley (Italy)

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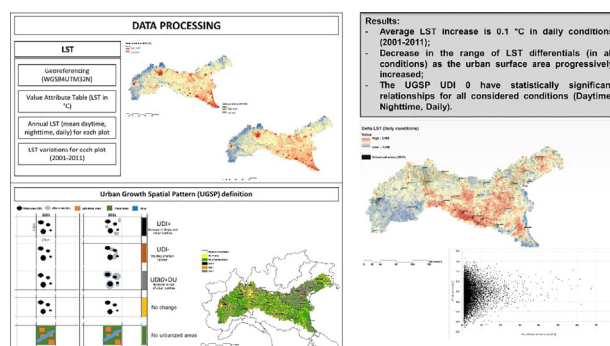
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HIGHLIGHTS

- Between 2001 and 2011, the Po Valley area saw an increase of 630 km² in urban areas.
- The prevailing model of urban growth is the UDI 0 (aggregated urban growth).
- The LST in daytime conditions was an average increase of +1,36 °C in the study area.
- Quantitative framework between increased urbanised areas and LST change performed.
- The UDI + (urban dispersion) shows an increase in the minimum differential recorded.

GRAPHICAL ABSTRACT



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ABSTRACT

Sealed surfaces greatly influence Urban Heat Island (UHI) effects. In this respect, both the composition and spatial patterns of anthropogenic land use play an important role in local thermal pattern. The urban environments' climate change adaptation strategy needs adequate knowledge systems urban planners can use to organise and design more resistant and resilient urban spaces. This study examined the relationship between Land Surface Temperature (LST) variations and increasing urbanised areas during the period 2001–2011 in the Po Valley, utilising different urban growth spatial patterns (UGSP). Remotely sensed LST data was obtained from MODIS (MODerate Resolution Imaging Spectroradiometer) at a resolution of 1 km/pixel for an 11 year-period, from 2001 to 2011, with urbanisation data from the ISTAT map (nominal scale 1:10,000) respectively for the 2001 and 2011 time sections. The relationship between dependent (mean annual daytime, nighttime and daily values) and independent (urbanised areas) variables were investigated through ANOVA test and post-hoc analysis ($p < 0.01$) for all defined UGSP. Results showed that there is a decreasing LST range (in all conditions) associated with progressive increase of urbanised areas. Furthermore, clustered patterns urban growth have a statistically significant relationship with daytime, nighttime and daily conditions while dispersed pattern urban growth have the same with nighttime only. The outcomes are helpful for understanding the effects of different UGSP, which have significant implications for urban planning, and identifying the critical territorial sectors in need of sustainable mitigation actions.

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1. Introduction

One of most important challenges for society and institutions is those to adapt the urban areas to the climate change currently

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underway. Climate change has become a constant topic in economic activities as well as for society, and has been recently added to the political agendas of many countries (UNFCCC - Paris COP21 - December 2015) with the awareness that a series of measures that cannot be delayed are necessary to seek to mitigate the effects. It is precisely the urban areas that suffer the greatest temperature increases, due mainly to Urban Heat Islands (UHI), whose effects are amplified by human activities (Santamouris, 2013). UHIs generate socioeconomic impacts on communities, all of which affect the quality of life (Yue and Xu, 2013; Rozos et al., 2013) of those living and working in urban areas (Wong et al., 2013; Dwivedi and Mohan, 2018; Macintyre et al., 2018). The intensity of the UHI phenomenon is expected to increase in the coming years, in parallel with the constant increase in the complexity of urbanisation, with significant repercussions on the conditions of urban life.

Recent studies in Po Valley (Tomozeiu et al., 2006; Ciccarelli et al., 2008; Stocker et al., 2013) have shown increases in average annual temperature from the second half of the twentieth century until today. The precipitation reduced by approximately 20%, which percentage increasing to 40 to 50% in the summer months, while the summers are always warmer. These changes inevitably influence soil-atmosphere exchanges, and as a consequence the hydrological cycle, with significant effects on river flows (Coppola et al., 2014; Vezzoli et al., 2015) and therefore on hydrogeological risk (Richts and Vrba, 2016). The economic and agricultural vulnerability of these territories inevitably increases (Bozzola and Swanson, 2014) with changes in crops (i.e., movement to the north of some crops such as olives, which has arrived in the Alps, or even the presence of grapevines at nearly 1200 m above sea level) loss of organic substance of soils, and increase in their aridification, with significant effects on the industrial area as well (i.e., damage to transport infrastructures, increase in temperature for cooling of systems), all considering that the Po Valley is home to 48% of industrial production and 35% of national agricultural production. These territories have also undergone a consistent loss of soil due to the intense urbanisation, which characterised Italy from the end of the Second World War until the early 2000s, and these areas have

seen a concentration of 40% of what is consumed in the entire country (Romano et al., 2017).

For these reasons, the main aim of this study was to provide quantitative framework on the LST variations resulting from different Urban Growth Spatial Patterns (UGSP) during the decade 2001–2011 in the Po Valley. The results will provide urban planners and decision-makers with information about the effects of new planned urban areas on the existing thermal patterns. This is a sustainable approach for useful management and planning in urban environments.

2. Study area

The Po Valley is one of the mid-lowlands of alluvial origin in southern Europe, stretching almost two degrees of latitude (from the 44th to the 46th parallel), from the southern side of the Alps to the far northern offshoots of the Apennines (Fig. 1). This morphological unit was formed by the eroded material of these mountain ranges, carried downstream by the waters melting away from shrinking glaciers, the debris of which has filled the subalpine basin. The plain extending from the Apennines in the south to the Alps in the north, including the northern Adriatic. The south-western border is formed by the Langhe and the Monferrato hills while the western border is represented by the Pre-Alps. The study area identified it was carried out using municipal administrative limits included in the aforementioned area. Besides being the most important agricultural area in Italy (35% of national agricultural production - 2017 data) and one of the most densely populated (at present over 21 million inhabitants, almost one = —third of the entire national population, with 361 inhab/km², almost double the national density) the Po Valley is also a major infrastructural junction for communications from the peninsular area to the North. It can be said that the Po Valley works essentially like a huge metropolis thanks to the high-speed railway (TAV) lines linking the major towns, taking the same amount of time as a city underground.

In the last 50 years, over 6000 km² of its land has been converted into urban areas, and current urban density is 15.6%, double the national

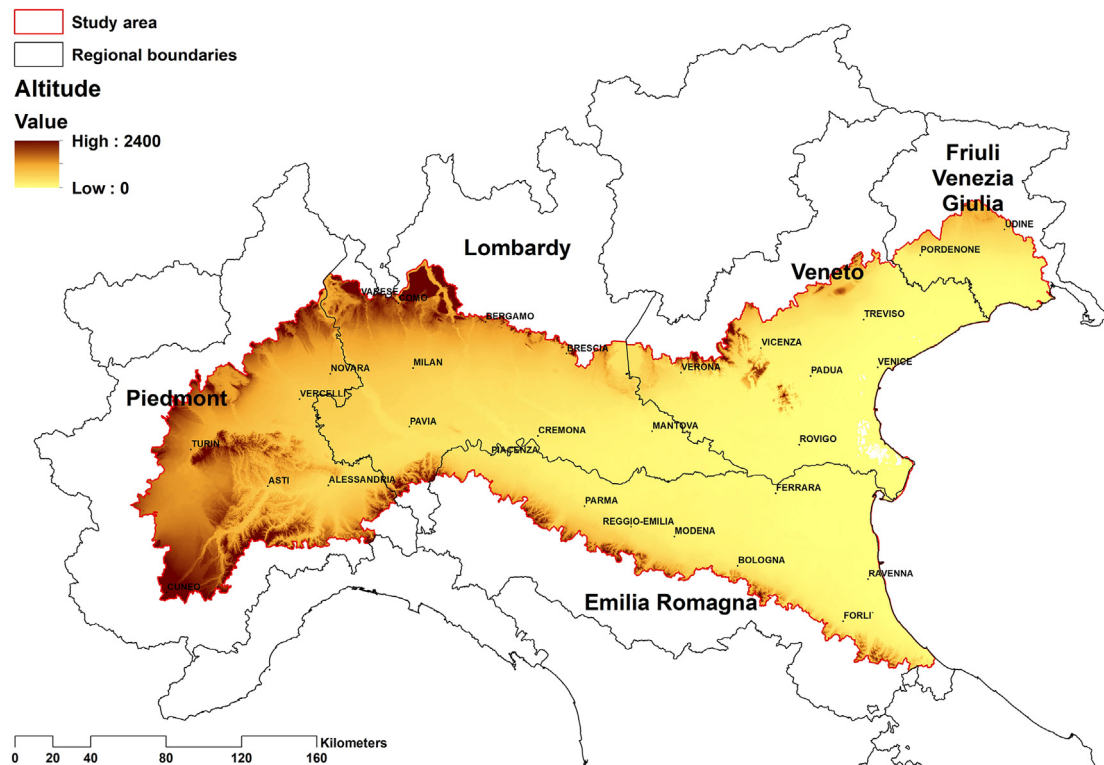


Fig. 1. Study area.

Table 1

Average Land Surface Temperature (LST) detected on the period 2002–2011. The table also shows the 95% confidence intervals and standard deviation.

Reference period (2002–2011)		Mean value (°C)	95% confidence intervals	Standard deviation
Annual	Daytime	20.2	19.6–20.8	1.38
	Nighttime	8.3	7.6–8.9	0.95
	Daily	14.3	13.9–14.7	0.88
Cool/cold period (from September to February)	Daytime	12.6	12.1–13.1	0.99
	Nighttime	3.1	2–3.2	1.03
	Daily	7.8	7.3–8.3	0.78
Warm/hot period (from March to August)	Daytime	27.2	26.6–27.8	1.75
	Nighttime	13.5	13.1–13.9	0.91
	Daily	20.5	20.1–20.9	1.05

density, currently calculated at approximately 7.5% (Romano and Zullo, 2016). The eastern border of the lowland is formed by nearly 300 km of coastline on the Adriatic sea, interspersed with lagoons and marshes formed by the estuaries of the major Alpine rivers (Isonzo, Tagliamento, Piave, Brenta, Adige and Po), the best known of which are the Lagoons of Grado and Venice and the Valli di Comacchio. According to Koppen-Geiger climate classification, the Po Valley is a “humid subtropical” (Cfa), characterised by hot and humid summers and mild winters. Some parts of the valley have a mild continental climate. Rainfall is between 700 and 1200 mm, depending on the area. Rainfall is concentrated in the spring and autumn months, but in the hot and humid summer there are frequent thunderstorms, especially north of the Po river. The annual range of climate is wide and is characterised by low average temperatures in winter and high in summer. Table 1 shows that the mean temperatures range from 3.1 (lowest mean value observed) to 12.6 during the cool/cold period and from 13.5 to 27.2 (highest mean value observed) during the warm/hot period.

3. Material and method

The study was conducted using the data for two distinct time sections (2001 and 2011). The urbanised surfaces come from the institutional ISTAT database (<https://www.istat.it/it/archivio/104317>) while the data on the LST were acquired from the NASA EarthData portal (<https://lpdaac.usgs.gov/>) both available in open format. In particular, the MODIS images, defined as MOD11A2, with geometric resolution of

1 km/pixel and a time resolution of 8 days, provide the LST values for both day and night. Just over 40 images were acquired for each year considered. LST is the radiant temperature measured at the interface between the surfaces of a material and the atmosphere, and it is considered a fundamental variable in calculating the radioactive budget (Ao et al., 2016) of surfaces in studies on potential climate change (Brivio et al., 2001). For subsequent statistical analyses, average nocturnal, diurnal, and daily temperature were taken into consideration for the entire year for the first time section investigated (2001) and for the period 2002–2011 for the second.

The urbanised surfaces were extracted from the sections of the ISTAT census data (2001–2011) acquired at a scale of 1:10,000 for the entire national territory. This data derives from the processing of the black and white AIMA orthophoto available with a ground resolution of 2 m for 2001 while for 2011 the colour AGEA (*Agenzia per le erogazioni in agricoltura* [Agency for Agricultural Subsidies]) orthophoto was used with a ground resolution of one meter. For purposes of this work, inhabited and manufacturing areas, according to ISTAT urban areas classification, were considered. The inhabited area (divided into inhabited centre, inhabited nucleus, and scattered houses, the latter is not considered, however, as they are not univocally identified) represents a more or less vast area of territory whose delimitation is obtained by drawing lines along the outside boundary of the buildings placed at the edges of a group of at least 15 buildings, including the related pertinent surfaces, accessory spaces (e.g. urban road network, parking) as well as the areas allocated for public green spaces (e.g. equipped green spaces).

A inhabited centre (or locality) is a group of houses located close to one another or with roads, squares or suchlike in between, or otherwise small gaps defined according to a variable value of approximately 70 m, and characterised by the existence of public services or enterprises (schools, offices, chemists, shops and suchlike) creating the condition for an independent social life and generally forming a gathering place where the inhabitants tend to congregate for religious, educational, business reasons or for obtaining provisions or suchlike, demonstrating the existence of a form of social life coordinated by the area itself. Tourist resorts, groups of chalets, hotels and similar accommodation used for tourism on a seasonal basis, are considered temporary localities, as long as they exhibit the features of a locality during the period of seasonal activity. A inhabited nucleus (or small inhabited areas) is an inhabited area, without the kind of gathering place that characterises a locality, formed by a group of houses close or attached to one another with at



Fig. 2. Urbanised areas from ISTAT map.

least five families, with roads, paths, squares, courtyards, small vegetable plots, small areas of uncultivated land and suchlike between them, on condition that the distance between houses does not exceed thirty metres and in any case is less than that between the nucleus itself and the closest of what are clearly scattered houses.

The production area, on the other hand, is a suburban area not included in the first with at least 10 local units (or with >200 employees)

contiguous or close to interposed roads, piazzas, and the like, or in any case short continuity solutions no >200 m, with a minimum surface area of 5 ha (Fig. 2). It should be noted that neither individual buildings nor individual local units are found. These entities fall within the perimeter of the areas that ISTAT calls “scattered houses” and which in fact are the complementary parts of the territory of each individual municipality.

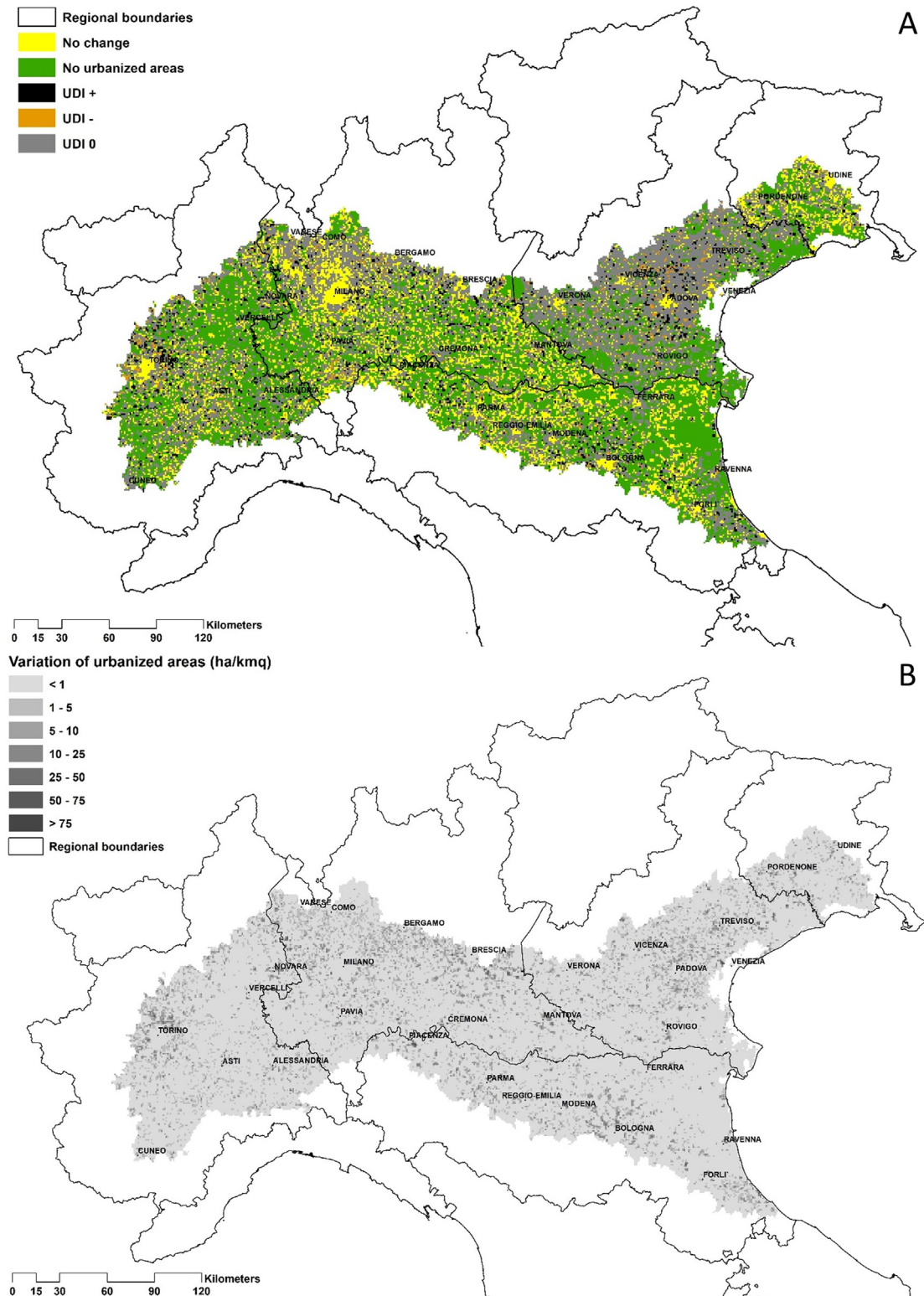


Fig. 3. UGSPs (A) and the variation of urbanised areas (B) for each analysed mesh.

Table 2
Minimum, mean and maximum delta LST values observed for each UGSPs.

		Daytime conditions			Nighttime conditions			Daily conditions		
		Minimum value	Mean value	Maximum value	Minimum value	Mean value	Maximum value	Minimum value	Mean value	Maximum value
UGSP	No urbanised areas	−0.96	1.33	3.74	−1.53	0.55	2.89	−0.56	0.92	2.24
	No change	−0.69	1.36	3.26	−2.75	0.57	2.35	−0.63	0.95	2.04
	UDI +	−0.32	1.33	2.91	−0.76	0.52	1.77	−0.03	0.93	2
	UDI −	0.19	1.33	3.02	−1.8	0.49	1.85	−0.06	0.9	1.9
	UDI 0	−0.95	1.39	4.52	−2.09	0.51	1.95	−1.14	0.94	2.06
	Study area	0.9	1.36	4.5	−2.75	0.53	2.89	−1.14	0.93	2.24

To compare with the LST data, the territory of the Po Valley was divided into vector meshes 1 km long corresponding to the spatial pattern of acquisition of the MODIS data. Each mesh was assigned a UGSP by calculating two specific indexes and the variation of their values through GIS spatial analysis techniques. In particular, the urban density (UD) index, expressed as square meters of urbanised surface for each mesh of 1 km² in its investigated time section, provides information on the amount of urban surface present for each km² of territory, while the UDI (Urban Dispersion Index) gives indications of the number of urban nuclei present for each km² of territory. A UDI increase over time (UGSP-UDI+) highlights the rise in the number of separate urban cores within the reference area and therefore always corresponds to an increase in dispersed urbanisation density (UD). A UDI drop (UGSP-UDI−), on the other hand, shows a reduction in separate urban cores and therefore the densification of existing ones with an increase in UD. When the UDI is constant (UGSP-UDI0), two conditions are possible: if UD increases (UD+), existing urban cores have grown in size, with new urbanised parts in contact with existing ones (UGSP-UDI0). If UD = 0 as well, there are no changes compared to the initial state (No change).

In all cases where there is an increase in urbanised surface, there is a change in the urban pattern that can therefore affect both the number of patches and their shape (UGSP - UDI +; UGSP - UDI−) or only the latter (UGSP - UDI 0). Furthermore, it is possible to affirm that urban growth through UDI + increases urban dispersion (sprinkling) while UDI − generates an aggregated urban pattern. Territories not affected by changes of an urban nature and without urbanised surfaces in both time sections investigated were associated with a different condition called “No urbanised areas”. Each plot was assigned 9 LST values distinguished as follows:

- LST 2001 (First full year of data acquisition from the MODIS sensor) - 3 values: annual average of the LST value for the three investigated conditions (Daytime, Nighttime and Daily)
- LST 2011 (3 values): average over the 2002–2011 period of the LST value for the three conditions investigated (Daytime, Nighttime and Daily);
- Delta LST (3 Values): difference between mean LST values registered for the two time sections on the three conditions investigated (Daytime, Nighttime and Daily)

Hence, the relationship between the dependent (mean daily, daytime, night time pixel-wise LST values) and independent (urbanised areas) variables was analysed using correlation analysis on the statistically significant urban spatial patterns at the one way ANOVA (Analysis Of Variance) test ($p < 0.01$), completed through post-hoc analysis. This analysis was conducted using the Tukey-Kramer test (controls Type I Error rate), a conservative, post hoc test used when the sample sizes for each level are unequal. This operation allowed paired comparisons between the LST differentials found in the various UGSPs and those recorded in the “No urbanised areas” condition taken as a reference. This comparison provides an indication of whether a given UGSP is influenced to a greater or lesser extent by the change in LST (daytime, nighttime and daily) recorded during the period. An integrated correlation analysis was also carried out on a set of statistical parameters for classes

of increase of urban surface area in the significant UGSPs during post-hoc analysis. The processing carried out made it possible to create a vector geographical database where each mesh shows the 9 LST values, the values of the two indices used for the identification of the UGSP, and the scope of urbanised surfaces realised.

4. Results

Between 2001 and 2011, the Po Valley area saw an increase of 630 km² in urban areas, corresponding to about 40% of the increase in the entire country (1620 km²). The density of urbanisation in the area in 2001 was 13.5%, then increasing by more than one percentage point (14.71%) in the next ten years. In 2011, >10% of the meshes considered had an urbanisation rate of >50%, more than half of which was over 75%, while those without urban surfaces decreased (over 1100 less than in 2001). Fig. 3A shows the associated UGSP and the variation of urbanised areas (Fig. 3B) for each analysed mesh. In almost all the territories, the prevailing model of urban growth is the one called UDI0 (especially in the Veneto region and in principal cities' hinterland), which avoided aggregated urban growth, while those associated with a significant dispersion (UGSP-UDI+) involves 5% of the study area.

Approximately 20% of the territory has undergone no urban change (no change) as these are already highly urbanised areas that are essentially related to all major urban centres. An analysis of climatic data shows that in daytime conditions there was an average increase in LST of +1.36 °C (minimum value of −0.9 °C, maximum °C value of 4.5 °C), in nighttime conditions the average increase in LST was +0.53 °C (minimum value of −2.75 °C, maximum value of 2.89 °C), while for daily conditions the average increase recorded was 0.93 °C (minimum value of −1.14 °C, maximum value of 2.24 °C) (Table 2) (Fig. 4).

The ANOVA test ($p < 0.01$) then showed statistically significant differences between the differentials found in the various UGSPs. We then proceeded, through post-hoc analysis performed with the Tukey-Kramer method ($K = 4 \text{ df} > 120$), to compare the averages of the differentials recorded in the various UGSPs with the one with the “No urbanised areas” condition. The results are shown in Table 3. The rows show the different comparisons while the columns show the different conditions analysed; the Q score is shown at the intersections of rows and columns (limit for significance equal to 4.40), while the columns highlighted in yellow show the statistically significant comparisons.

A correlation analysis was therefore carried out between the increase in urban surface area (variations of >1 ha corresponding to an increase of one percentage point in the density of urbanisation of the mesh considered) and the LST differential only for the models that were statistically significant in previous comparisons.

4.1. Urbanised areas related to annual mean daytime conditions

According to Table 3, the correlation between the variation of urbanised areas and delta LST was analysed, for UGSP-UDI0 only.

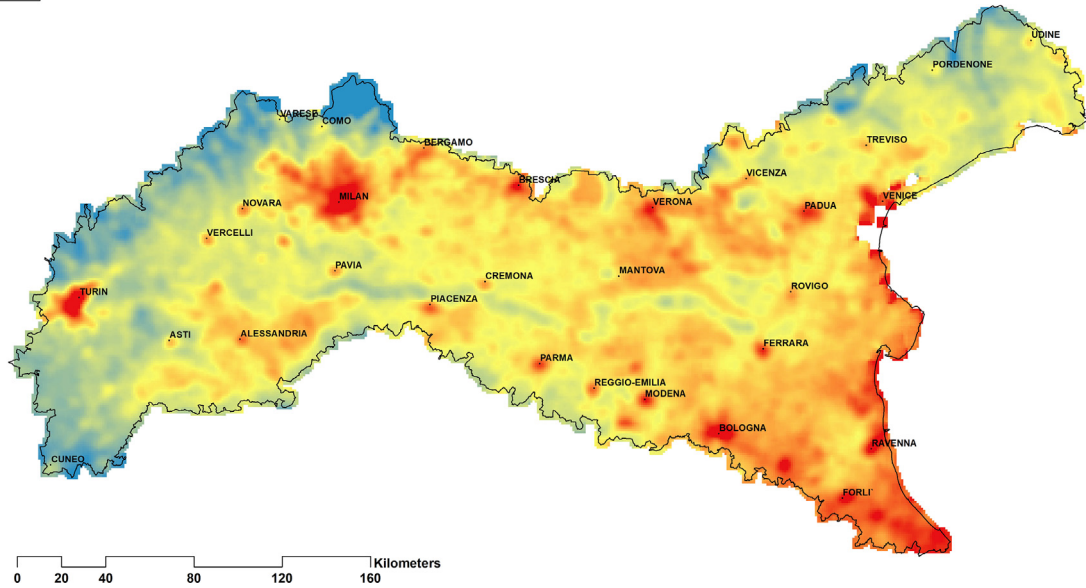
The Fig. 5 shows that both the standard deviation and variance decrease with the increase of urbanised surface. Essentially, the

LST 2001 (Daily conditions)

Value °C



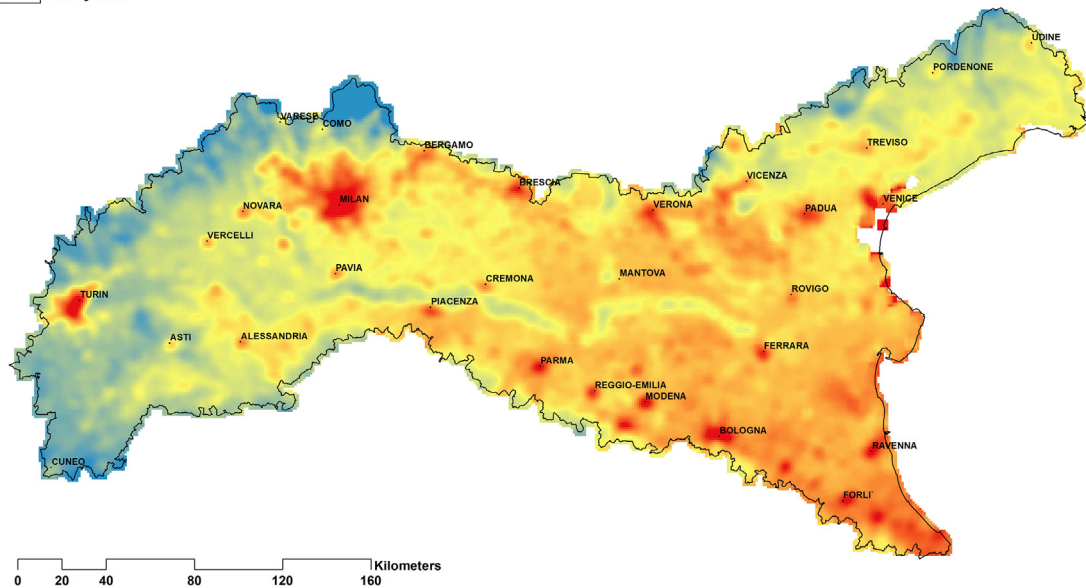
Study area

**LST 2011 (Daily conditions)**

Value °C



Study area

**Fig. 4.** LST values in the 2001 section (A) and in 2011 (B) for daily conditions.

range of values assumed by the LST is smaller as the urban coverage progressively increases. Pearson's linear correlation index always assumes low values in the urban density classes identified, while it is interesting to note the increase in the minimum recorded LST value, which goes from negative to positive for values higher than

20 ha/km². The average value increases along with urban density and, in particular, there is a 0.3 °C difference between meshes with an increase of urban area of the 40 ha/km² and those with <10 ha/km² of urbanised surface. The maximum values found are always >2.3 °C.

Table 3

Q values derived from post-hoc analysis.

	Daytime conditions	Nighttime conditions	Daily conditions
No urbanised areas - UDI +	0.42	5.23	2.11
No urbanised areas - UDI 0	15.66	19.60	10.14
No urbanised areas - UDI –	0.60	9.13	2.18

4.2. Urbanised areas related to annual mean nighttime conditions

This relation was analysed for all UGSPs. The analysis of the UDI+ data (Fig. 6) shows no variation in the average values in the different urban density classes ($+0.5^{\circ}\text{C}$), while it is important to emphasise the increase in the minimum LST values as the urbanised areas increase. The Pearson index shows a weak linear, but not statistically significant, correlation in the meshes with an increase in urban surface area equal to 30–40 ha/km^2 (approximately 0.2).

For UDI0 as well (Fig. 7), there were no variations recorded in the average values in the different classes of urban density, which was 0.5°C . The trend of the minimum LST values is different from the previous one, the only positive value was recorded in the meshes with an increase in urban area between 30 and 40 ha. On the other hand, it is possible to show a progressive decrease in the maximum LST values as the urban surface area increases. The Pearson index shows a weak, but not statistically significant correlation in this case as well, in meshes with the increase in urban area is $>40 \text{ ha}/\text{km}^2$. In meshes where urban growth has led to the connection of nuclei (UDI –) (Fig. 8) there are positive minimum values for increases in urban coverage $>30 \text{ ha}/\text{km}^2$ while the average value remains substantially invariant.

4.3. Urbanised areas related to annual mean daily conditions

The only data analysed for this relationship concerns UGSP- UDI0. The average differential LST values show 1°C with a difference of 0.2°C between meshes with an increase in urbanised surfaces

$<10 \text{ ha}/\text{km}^2$ and those that exceed $40 \text{ ha}/\text{km}^2$. The minimum values recorded increase simultaneously with the increase in urbanised surface (Fig. 9). The Pearson index shows no linear correlation between the two variables in the different classes.

5. Discussion

The study conducted highlighted the effects of the various UGSPs on LST under the various conditions considered over a period of 10 years for an area that is both climatically and morphologically homogeneous such as the Po Valley. With regard to the LST values considered, it should be noted that the possible annual variability of temperatures was reduced, as the values assigned to 2011 derive from the 10-year average of findings for all conditions considered. Urban surface data comes from the same information source (ISTAT), has the same characteristics with regard to cartographic acquisition methods, and has a good thematic resolution. However, as already specified above, the considered urbanised areas could contain various green areas or different types of soil within their perimeters (see Fig. 2) that can have direct and indirect effects on the local climate (Georgi and Dimitriou, 2010; Hamada and Ohta, 2010; Kong et al., 2014; Zhang et al., 2017; Huang et al., 2018; De Munck et al., 2018). We have not used the Corine Land Cover (CLC) data because totally unsuitable for capturing the phenomenon of Italian urbanisation, which is extremely scattered, with extremely small settlements made up of numerous miniscule nuclei or even individual buildings spread over an enormous surface. The CLC data cartographic acquisition methods do not detect these urban areas. Using CLC methodology, the minimum mappable unit is equal to 25 ha

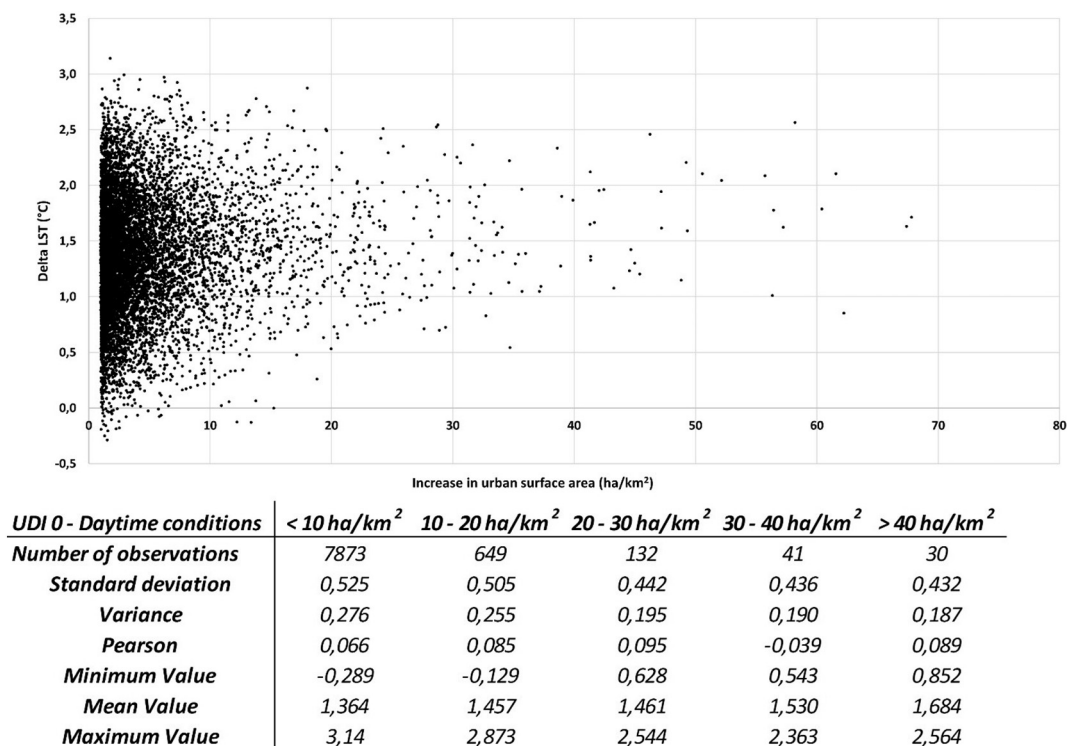


Fig. 5. Statistical outcomes of correlation analysis between LST and variation of urban areas (ha) per km^2 in study area (UDI0 – Daytime conditions).

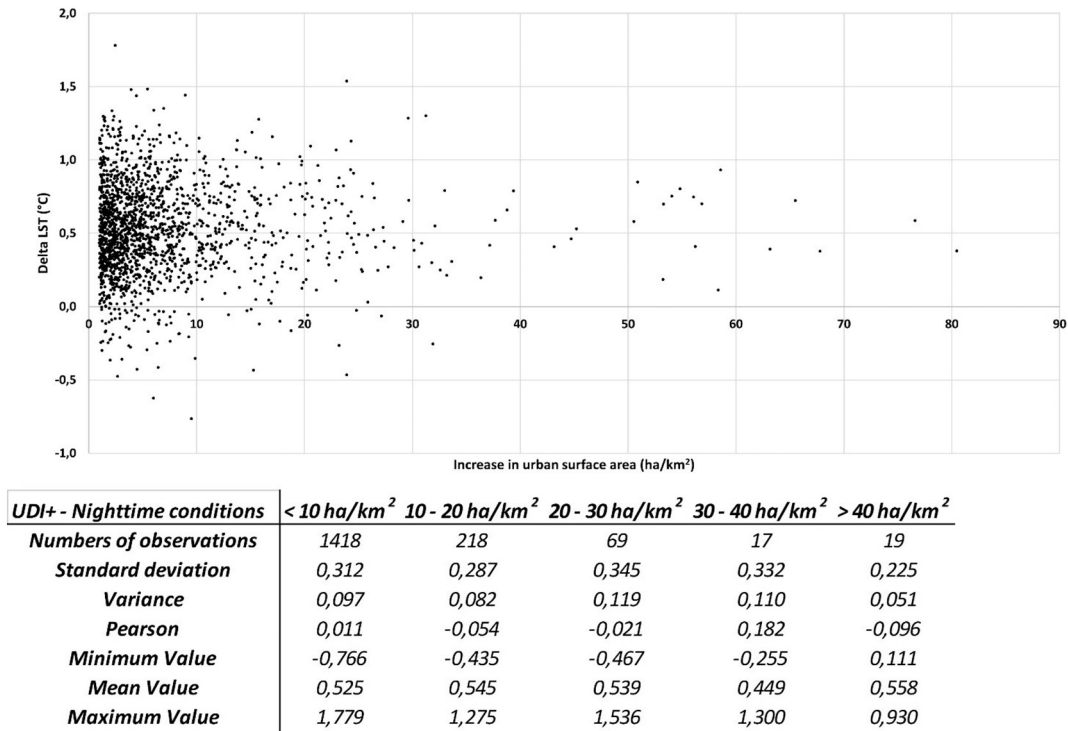


Fig. 6. Statistical outcomes of correlation analysis between LST and variation of urban areas (ha) per km² in study area (UDI+ - Nighttime conditions).

(equivalent to a circle of 2.8 mm at a scale of 1:100,000) and the minimum width of the polygons is 100 m (1 mm at nominal scale). In addition, the use of the prevalent and secondary soil for each of these areas, identified from photointerpretation of the digital orthophotos of flight IT2000, was defined. The soil covering the greatest surface area inside the circle of radius 400 m was used as the prevalent soil. This resulted

in an analysis that was quite approximate regarding identification, and as such delimitation, of the urbanised land surfaces: the areas smaller than 25 ha do not appear in the final calculation, in the same manner as aggregates of houses that have boundaries of <100 m (scattered houses, small aggregates). The secondary viability (state, provincial, municipal roads) cannot be considered for obvious technical reasons.

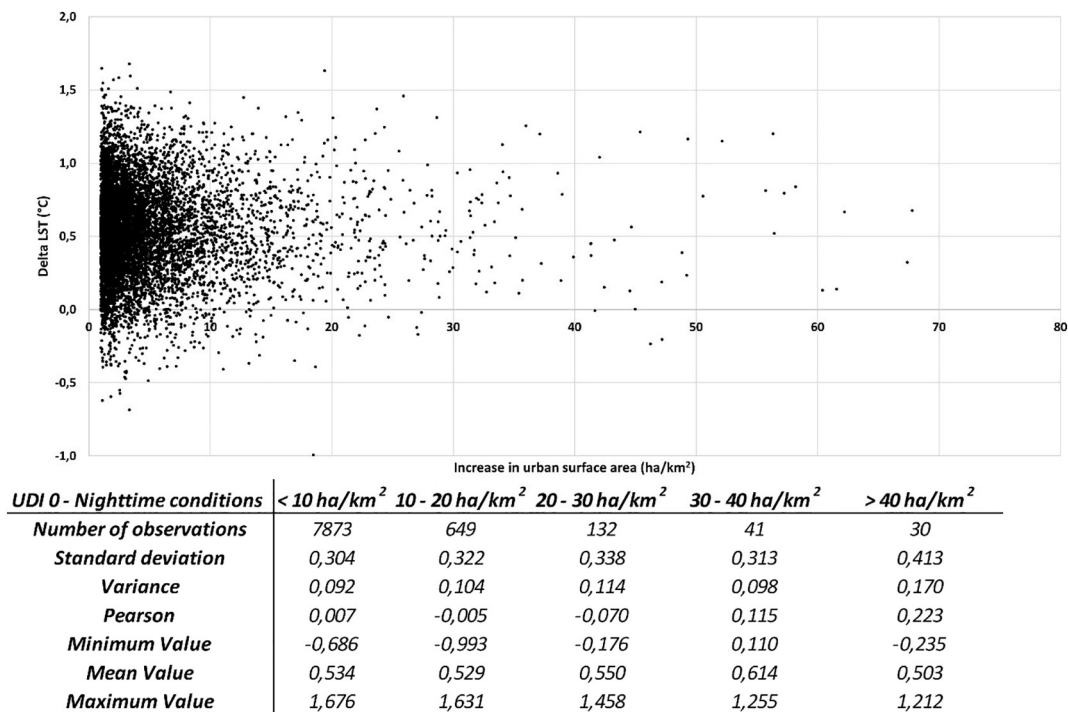


Fig. 7. Statistical outcomes of correlation analysis between LST and variation of urban areas (ha) per km² in study area (UDI0 - Nighttime conditions).

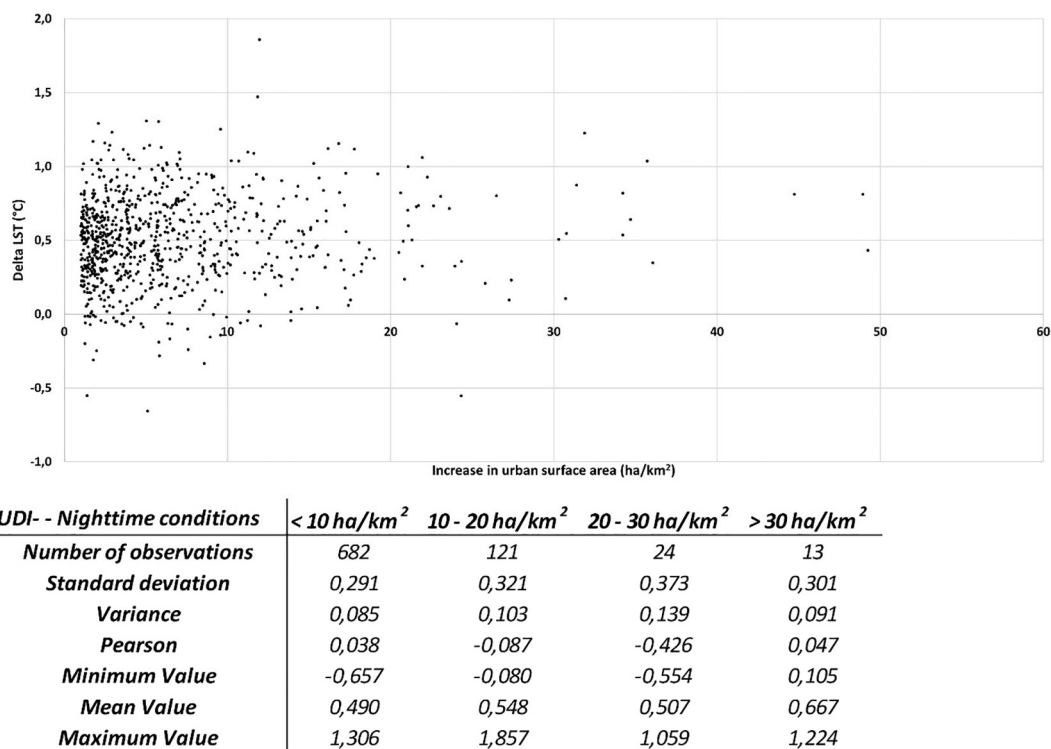


Fig. 8. Statistical outcomes of correlation analysis between LST and variation of urban areas (ha) per km² in study area (UDI - Nighttime conditions).

The proof of the statements just made lies in the fact that the urban density for the Po Valley deriving from CLC data from 2010 is equal to 11,1% while the same parameter deriving from ISTAT census data is almost 15%.

Furthermore, we do not investigate Floor Area Ratio (FAR), building density, and its variations within urbanised areas because this data is not available for all regions. However, these variables could influence the UHI, especially in daytime conditions (Lin et al., 2017). That said,

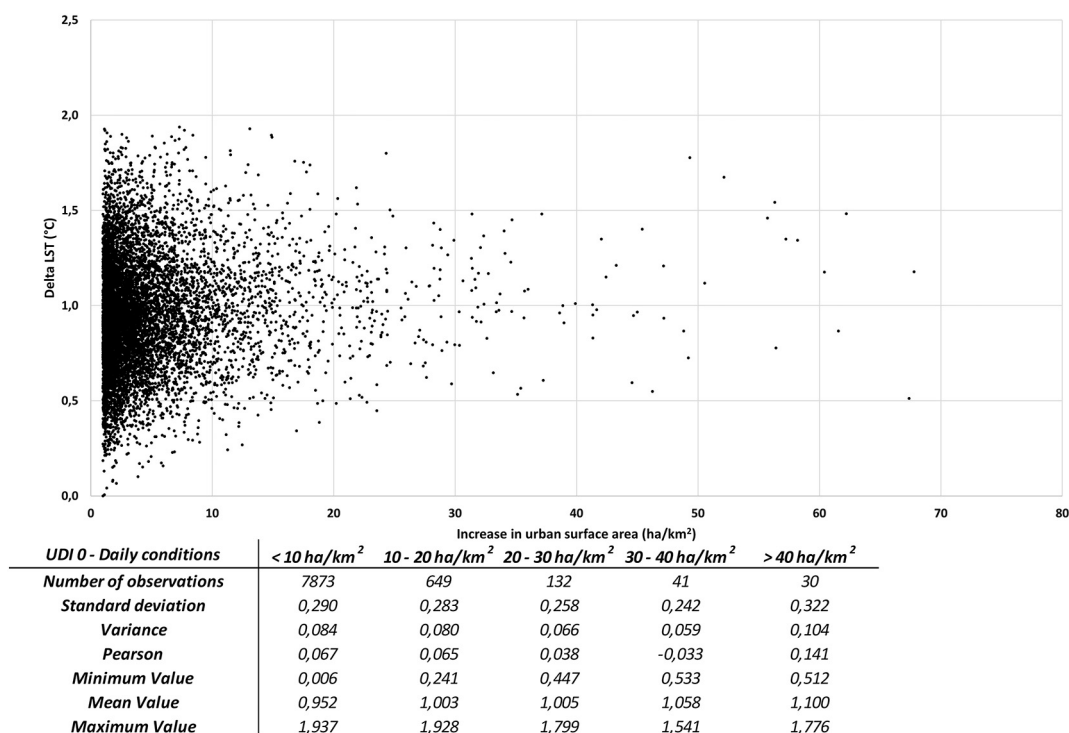


Fig. 9. Statistical outcomes of correlation analysis between LST and variation of urban areas (ha) per km² in study area (UDI0 - Daily conditions).

the results show that in the Po Valley the prevailing UGSP was UD10, with a consequent aggregated urban growth. Moreover, the intensity of urban sprinkling (UGSP UD1 +) has also increased over the decade investigated. The damage caused by this model of urban growth to the landscape, environment, and communities is much more serious and irreversible than what is notoriously caused by urban sprawl (Romano et al., 2017). Urban sprawl has been recognized as a territorial disease (Squires, 2002; European Commission, 2006; The Worldwatch Institute, 2007; Ewing, 2008; Angel et al., 2012; Barrington-Leigh and Millard-Ballb, 2015; Paleari, 2017) has effects that branch out to various issues and at various scales (Haase and Nuissl, 2007; Li et al., 2016; Smidt et al., 2018; Xu et al., 2018).

Many studies have dealt with the thermal impacts tied to the increase of urban surfaces (Shahmohamadi et al., 2010; Kim et al., 2016; Chen et al., 2017; Privitera et al., 2018; Yin et al., 2018) and in particular, on the local scale, the effects of urban heat islands (McCarthy et al., 2010; Xu et al., 2010; Zhang et al., 2010; Yang et al., 2013). Most previous studies have confirmed that there is a scaling effect on the relationship between urban land-use patterns and LSTs (Voogt and Oke, 2003; Liu and Weng, 2009; Keramitsoglou et al., 2011; Li et al., 2012; Van Nguyen et al., 2015). Indeed, the relationships between urbanised areas and LST thermal pattern variations are spatially different in the study area. In particular, even if the prevalent UGSP model is the same (UD10) both for big urban areas and for smaller centers, the correlation is stronger for the first ones (i.e. R^2 for Milan is 0,65 in daily conditions) than the second ones. In Italy, a few studies have investigated the relationship between urban built-up surfaces and LST variations (Morabito et al., 2016; Bonafoni et al., 2017a, 2017b) or they have conducted building-proxy thermal analyses (Morabito et al., 2018) but only in a few cities and without taking urban spatial patterns into account. In our study it was possible to observe, essentially for all the conditions investigated, a decrease in the range of LST differentials as the urban surface area progressively increased. In the UGSP - UD10, in daytime conditions, for increases in urban surface of >20 ha/km², the minimum differential recorded increases and assumes positive values (below

20 ha/km² negative minimum values have been recorded), as well as the average differential that increases with the progressive increase in urban area. In nighttime conditions, the UD1 + dispersed form of growth model shows an increase in the minimum differential recorded, from negative to positive for increases of >40 ha/km² of urban surface area. Again with reference to nighttime temperatures, in areas where urban growth has taken place in a clustered form through the UD10 model, a decrease in the maximum value of the LST delta has been observed as the urban surface has progressively increased.

Our research represents an innovative contribution to recent studies on urban climate providing a quantitative framework for the relationship between increased urbanised areas and LST change in the different UGSPs. As of LST changes, The analysis showed that, over the past 10 years in the Po Valley, the average temperature increased in some areas even >2 °C (in daily conditions) (Fig. 10). The findings of this work are of great importance as they provide useful information for increasing the public awareness of the different urban thermal change deriving from different urban growth spatial patterns at the local scale. Indeed, as demonstrated in this study, different UGSPs have differently impact both on the urban microclimate and on the UHI effect. Furthermore, in the Strategic Environmental Assessment (SEA) of the city plans process, is possible ex ante evaluating the impacts on the urban microclimate and on the UHI effect of the planned urbanised areas through the formulation of different scenarios. This could support more sustainable land management practices in the urban environment and enhance the quality of life of the population.

6. Conclusion

This research provides an interesting and innovative contribution for understanding the relationships between urban growth spatial patterns and the urban thermal environment. The Po Valley, which is both climatically and morphologically homogeneous, provided an ideal test case for the influence of urban clusters. Particularly, we were demonstrated that different UGSPs have had a different effect on the exiting

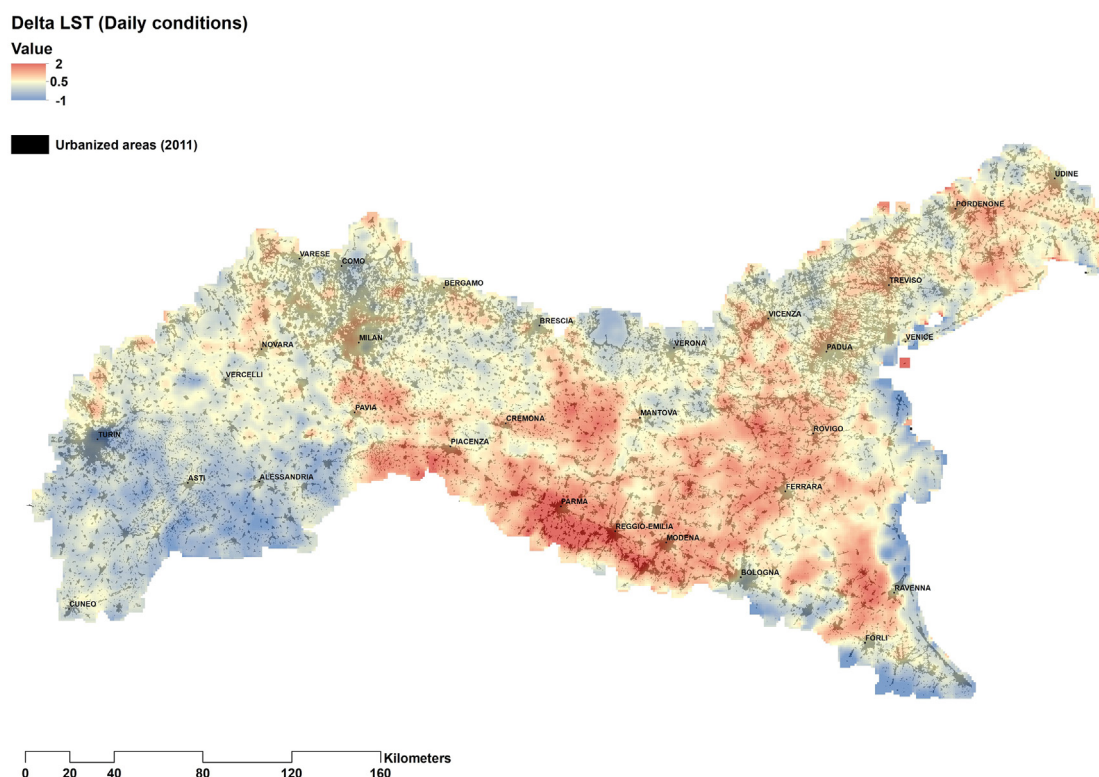


Fig. 10. Delta mean LST in the study area (2001–2011) on daily conditions.

urban thermal pattern. Furthermore, our findings are useful for better understanding the complex dynamics of the urban climate. The outcomes can be used to allocate new urbanised surfaces, optimising their distribution so as to decrease the effects of UHIs, through the tools of territorial governance, appropriately calibrating objectives and actions. It is necessary, especially for aggregated urban patterns, various mitigation actions to be applied at the level of urban design such as for example the use of cool material (Synnefa et al., 2008), green roofs (Odli et al., 2016; Sharma et al., 2016; Battista et al., 2016a, 2016b; Dwivedi and Mohan, 2018) and creating dense urban vertical green cover or forests (Gunawardena et al., 2017). Together with these, appropriate urban renewal and urban green infrastructure projects should be applied, to increase cooling effects and consequently decrease runoff coefficients, in accordance with the National Strategy for Adaptation to Climate Change (Castellari et al., 2014). In this way it is possible to increase the resilience and resistance of various urban environments to both climate change and the effects of UHI. Further research opportunities regarding the study of Annual Cycle Parameters (ACP) for the Po Valley to investigate the climatic variability at the urban scale through estimating LST patterns under largely cloud-free conditions (Bechtel, 2012; Bechtel et al., 2013; Bechtel, 2016). Future work will examine the relationship between urban growth and the seasonal LST variation. Further, it could be interesting to investigate this relationship through a downscaling process with ASTER sensor data (geometric resolution of 90 m/pixel) especially for larger urban areas.

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